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DEVELOPMENT OF LIQUID OXYGEN EXPLOSIVES DURING THE WAR

BY

GEORGE S. RICE

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PREFACE.

The increasing cost of dynamite and permissible explosives at the time the United States entered the great war caused the Bureau of Mines to investigate all possible substitutes. The author of this paper called attention to the possibilities of liquid oxygen and carbonaceous material as an explosive compound to serve as a substitute for black blasting powder and dynamite in certain kinds of mining and quarrying work. The raw materials—oxygen and carbon—are unlimited in quantity, and production requires merely power and suitable apparatus for liquefying the oxygen of the air.

This kind of explosive was first used experimentally in Germany under the name of "oxyliquit." It was tested in an early form at the Simplon Tunnel (Switzerland) about 1899, and although the claim was that the tests were favorable, it evidently was not a decided success commercially with the methods then used. Apparently one of the troubles then not realized was that the oxygen used was not pure enough, but contained too much nitrogen. In fact, the earliest experiments were with liquid air, more or less self-enriched by standing, the nitrogen evaporating faster than the oxygen.

The bureau began its testing of liquid oxygen explosive in April, 1917, and experimental results, as reported in this paper were decidedly favorable, but owing to the difficulty of obtaining suitable liquid oxygen manufacturing machinery and the necessity of concentrating the bureau's explosives investigations on military explosives, further experiments had to be postponed for a while.

Following the armistice, the Secretary of the Interior and the Director of the Bureau of Mines decided to send a committee of Bureau of Mines engineers and metallurgists to Europe to observe the progress in the special industries under the stimulus of war, and the author of this paper, as chief mining engineer, was asked to particularly observe the progress that had been made with liquid oxygen explosive.

Mr. Rice reports that the Germans used liquid oxygen explosive extensively in nongaseous coal mines, in quarrying, and in iron mines, as well as for destructive purposes in French steel plants. At several Lorraine minette iron ore mines the Germans had installed in a permanent manner liquid oxygen explosives apparatus for mining the ore. Other European countries were not found to have used liquid oxygen explosive.

The bureau will again resume its experimental investigations with a view to making the use of liquid oxygen explosive practicable in appropriate mining and quarrying operations. As eminent physicists are promising great improvements in liquefying apparatus that can be used for the production of cheap oxygen, it is possible that the explosive may become, with all its disadvantages, so cheap that it will supplement other explosives where conditions permit its use.

As soon as the necessary experiments have been made a bulletin will be issued giving the details of the experiments.

Van. H. Manning,
Director.

DEVELOPMENT OF LIQUID OXYGEN EXPLOSIVES DURING THE WAR.

By George S. Rice.

INTRODUCTION.

This preliminary report briefly sets forth information gathered by the Bureau of Mines in its investigation of liquid oxygen explosives. It describes the developments in the use of such explosives during the war, gives the essential results of experiments conducted by the bureau, the observations on liquid explosives of a bureau committee sent abroad, and discusses the possibilities of applying the explosives to mining in this country.

ACKNOWLEDGMENTS.

The author wishes to express his appreciation of the valuable investigative work conducted by S. P. Howell, explosives engineer, and his former assistant J. L. Sherrick, who not only carried on the testing work, but have in preparation a detailed report of the methods employed and fundamental principles involved. This report will be enlarged after further practical tests, and will be published as a bulletin of the bureau.

HISTORICAL REVIEW.

In the course of the great war glycerin and ammonia became scarce and after the United States entered the war the scarcity became more acute. This scarcity affected the production of nitroglycerin, ammonia dynamites, and permissible explosives, greatly increased their cost to the mining industry, and caused the United States Bureau of Mines to look for substitutes. That which seemed to offer possibilities was liquid oxygen in conjunction with carbonaceous matter, especially because it does not require nitrates as do most commercial explosives, including black powder.

Oxygen, when more or less pure, if intimately mixed in proper proportions with finely divided carbon or carbonaceous material will, when ignited, unite chemically with such rapidity as to develop great explosive force. The more condensed are the oxygen and carbon particles, the more violent is the explosion. Oxygen is most condensed in liquid form, but, on the other hand, it remains in that form only at a very low temperature (boiling point −183° C.) for the comparatively short period while it is evaporating. This is the principal deterrent and the only important one to using it more freely. To overcome this handicap, special methods in use are necessary, as well as special apparatus. Liquid oxygen is a bluish liquid of a density of 1.118, is strongly magnetic, boils at −183° C. and freezes at −225° C.

Liquid "air,"[a] in which the normal oxygen content was more or less increased, in mixture with carbonaceous material was first tried as an explosive in Germany, in 1897, following the invention by Linde of his liquefying apparatus in 1895, blasting tests being conducted with favorable results in a crosscut of the Penzberg coal mine in upper Bavaria.

In the first tests a paste of charcoal and liquid air was insulated with sheep's wool and put directly into drill holes. It was found, however, that the natural rock heat caused the liquid air to evaporate rapidly and the blasting effects were slight. The mixture was then put into insulating paper wrappers and exploded through the agency of cap and fuse, but because of the danger of premature ignition from the outward burning fuse in the presence of the constantly evaporating oxygen, the fuses were impregnated with an incombustible substance.[b] Sulphur was also tried as a part of the mixture to increase the blasting effect. The effect of this addition is not reported by Seider,[c] who describes the tests in a paper published March 15, 1906. He states that although the Penzberg tests were considered satisfactory in general, difficulties arose in manipulation.

In 1898 a German patent was granted for the explosive under the name of "oxyliquit." Various kinds of charcoal were tried as the carbonaceous material. Cotton was impregnated with charcoal and placed in wrapping paper wound spirally in several layers and liquid "air" introduced through filter-paper tubes extending to the bottom of the cartridge. In other tests prepared cartridges were immersed in the liquid air to saturate them before insertion in the drill hole.

It was found that unless liquid air rich in oxygen was employed, the explosive was unreliable because of explosions not being uniform.

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[a] Normal dry air is a mechanical mixture having the average composition, as given by Mellor (Modern Inorganic Chemistry, p. 560) as follows:

		By weight.	By volume.
Nitrogen	per cent	75. 51	78. 03
Oxygen	do	23. 15	20. 99
Inert gases (argon principally)	do	1. 30	0. 95
Carbon dioxide	do	0. 04	0. 03

The "inert" gases are ordinarily grouped with nitrogen. Density of liquid nitrogen according to Dewarr 0.8042. Liquid oxygen density according to Roscoe is 1.1181. The density of liquid air would be in accordance with the proportions in the mixture.

[b] Later this was found not to be important in rock blasting and in iron mining. (Author.)

[c] Seider, Ludwig, Oxyliquit: Ztschr. ges. Schiess- und Sprengstoffwesen, vol. 1, Mar. 15, 1906, pp. 87–89.

In 1898 tests were made in a factory at Schlebusch, in the use of oxyliquit in the presence of gas and coal dust mixtures, to determine whether it was safe to use in gaseous coal mines, but ignition was obtained. [Similar results were recently obtained at the Pittsburgh testing station of the bureau, so oxyliquit can not be considered as a substitute for " permissible " explosives for use in gaseous mines.]

Various substances were tried, such as wood dust, wheat flour, potassium nitrate, ammonium nitrate, and soot. As the absorption capacity of most of these substances is very small, they were mixed with kieselguhr. Petroleum was tried as the carbon carrier in conjunction with the kieselguhr and an explosive was obtained which met the full requirement of free detonation. Comment was made by Seider, in his paper mentioned above, that kieselguhr, apart from its great absorption capacity, which enables it to absorb twice its weight of liquid oxygen, consists of sharp-edged and hard siliceous skeletons of diatoms, and hence is well fitted for the transmission of impact or detonation. It was found possible by transmitted explosion to cause the explosion of two cartridges with a small interval between them. Coke charcoal proved to be an equally good absorbent and had the advantage of not introducing an incombustible material.

The explosive is cheaper than other explosives, according to Seider. He gives the following figures:

Seider's figures on cost of oxyliquit, Germany, 1906.

	Cost (Prewar exchange).	
	Marks.	Cents.
500 grams liquid oxygen	0.15	4
300 grams kieselguhr	0.04	1
200 grams petroleum	0.07	1¾
Wrappers	0.09	2¼
1 kilogram oxyliquit	0.35	9

The first important trials of oxyliquit were made in driving the Simplon Tunnel; the mixture there used was crude petroleum, soot, and kieselguhr, in the proportions of 20, 30, and 50, respectively. The strength was reported to be equal to that of blasting gelatin. The firing was carried out in drill holes 3 to 4 inches in diameter, mixtures of various carbonaceous materials being used. In spite of the results obtained, which Seider says were favorable, the use of oxyliquit was stopped after the death of Engineer Brandt, who was in charge of the experimental work. Comparative strength tests made in a Bichel gage at Neubabelsberg, Germany, gave the following weights to obtain a pressure of 40 kilograms per square centimeter, as reported by Seider.

Weights of different explosives needed to give pressure of 40 kilograms per square centimeter.[a]

	Grams.
Burnt cork, petroleum, and liquid oxygen	58
Kieselguhr, petroleum, and liquid oxygen	115
Blasting gelatin	86
Gelatin dynamite	102
Carbonite	170
Blasting powder	283
Simplon Tunnel mixture	84

The analysis of the gaseous products of combustion from the Bichel gage showed: Carbon dioxide, 66 per cent; oxygen, none; carbon monoxide, 2 per cent; and nitrogen, 32 per cent.

The analysis shows that the combustion was complete. The testing chamber was filled with air at the time of firing, which accounts for the considerable proportion of nitrogen in the sample.

In spite of the claimed favorable results obtained in the Simplon Tunnel, no extensive testing seems to have been carried on for many years.

Meantime, in 1900, Claude, of France, invented another type of air-liquefying apparatus which was considered, theoretically at least, superior to the Linde, and patented the rectification principle. Linde in 1902 designed his rectification apparatus. Both types of apparatus, the Linde and the Claude, and particularly the Linde are extensively employed in different countries in the production of various highly compressed gases for commercial uses by low-temperature fractional distillation, such as liquid oxygen, liquid hydrogen, and liquid carbonic acid. In 1904 Sir James Dewar, of Great Britain, invented the method of producing, by the presence of charcoal, a high vacuum in a double-walled chamber—the Dewar flask—which advanced the art by giving a container which greatly decreased the rate of evaporation of stored liquefied gases.

Apparently little attention was given to the further development of methods of practical application of liquid oxygen for blasting purposes until the beginning of the great war; the liquefying apparatus which has been so extensively used for producing compressed oxygen from air was arranged primarily for this purpose rather than for making a liquid product which would not stand transportation and could not be kept in liquefied form for any great length of time without very great loss of energy. One of the few developments in connection with the application of liquid oxygen was for use in a certain mine-rescue breathing apparatus (aerolith). A few mine-rescue stations in Great Britain have been equipped with this apparatus, but the requirement of having to keep the liquefying machine running continuously for that purpose only was an obstacle to its more extensive introduction. If other uses for liquid oxygen at a mining plant were found, they would largely remove this obstacle to employment of a type of mine rescue apparatus not without distinct merits.

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[a] Similar favorable results for various oxygen mixtures were shown in the comparative strength tests conducted in the ballistic pendulum by the Bureau of Mines at its Pittsburgh station. See pp. 13, 14.

When Germany found that the war would be long, her technical officials, in order to conserve the limited supplies of glycerin and stocks of Chilean nitrates—the latter being important for fertilizers as well as for various types of military explosives—began to look for substitutes for these materials for mining purposes.

An account in Stahl and Eisen, November, 1915, described the practical use of liquid oxygen explosive in three coal mines in upper Silesia, and alleged that the blasting work could be done at a cost equal to that when dynamite was used at a price equivalent to about 12 cents per pound of dynamite.

Evidently there had been difficulties in the rapid extension of use, but casual reports received from time to time by American observers indicate that the use of liquid oxygen explosive was widely extended in Germany before the United States entered the war. Maj. Gen. Kuhn, formerly military attaché of the American Embassy in Berlin just before the United States entered the war, informed the writer that it was then being used for excavating subways in Berlin. Dr. Alonzo B. Taylor, of the United States Food Administration, advised that he had observed similar uses.

BUREAU OF MINES EXPERIMENTS.

Experiments on liquid oxygen explosive were begun in March, 1917, at the bureau's testing station at Pittsburgh, Pa., by J. L. Sherrick, directed by S. P. Howell, explosives enginer, and under the general supervision of the author. This work, starting with such earlier data as was then available, aimed to develop the technique of use and to compare the strength with that of standard dynamite, also to determine whether or not the explosive would be safe to use in a gaseous coal mine.

It will not be possible within the compass of this paper to give all the details of the bureau's experimental work, which will be given in later publications, but the chief results were as follows: The trial of various carbonaceous materials mixed with liquid oxygen of different degrees of purity and placed in special cartridges, the design and construction of an excellent soaking container of the vacuum-bottle type, and the testing of the explosive in the standard apparatus as well as in the blasting of rock in quarries.

Among other carbonaceous materials tested, lamp black, wood pulp, and crude petroleum were tried in various proportions. The material or mixture to be tested is contained in a cylindrical sack of cheesecloth, seven-eighths of an inch to 1 inch in diameter. An electric detonator is placed in the end of the sack. It is then dipped in the soaking receptacle into which liquid oxygen has been previously poured from the shipping container—a large Dewar flask. The soaking takes 10 to 15 minutes. Then the sack is inserted in a pasteboard tube with closed end, the tube having been chilled by dipping in the oxygen. A tubular cover of equal length is placed over the tube, giving a double-walled container.

The pasteboard container and cheesecloth must be included in figuring the weight of the carbonaceous material, to obtain the proper chemical balance between the amount of carbon and the amount of liquid oxygen. This is necessary in order to insure that combustion will be as nearly complete as possible, for maximum efficiency, and also that the fumes from the explosion will be CO_2 rather than poisonous CO. To this end less carbonaceous matter by weight is required than oxygen. Moreover, at the moment of completion of dipping, the explosive must contain enough excess oxygen to offset the amount that vaporizes during the 10 minutes allowed for placing charges in several drill holes, for connecting the leads, and for the miners to gain a safe place before firing.

To obtain the absorption of the needed amount of oxygen for the chemical balance and to prevent an excess of carbon and consequent burning to CO, it is necessary that the carbonaceous material be a loosely compacted substance like cotton or wood pulp or else that an inert absorptive material be mixed with the carbonaceous material. In other words, the quantity of oxygen which can be held in a given volume determines the amount of carbon which is used. One of the best absorbers proved to be kieselguhr, which also proved to be one of the best for retarding the rapid evaporation of the liquid oxygen.

In the tests the proportions of different carbonaceous materials and kieselguhr were varied and the relative efficiencies were determined. The analyses of samples tested in the ballistic pendulum which are given hereafter, indicate the results of some of the variations of carbon mixtures.

The procedure in loading a hole for blasting was as follows:

A No. 6 detonator is placed in the inner cartridge—the cheesecloth sack—and this is soaked in liquid oxygen for 10 to 15 minutes. On removal, the inner cartridge is found to be frozen stiff, it is then slipped into the telescopic pasteboard container, which has also been chilled by dipping in the liquid oxygen. The assembled cartridge is inserted into the hole and a wad of cotton placed on it. A brass tube 3 mm. in internal diameter, is then placed in the hole, extending from the cartridge to the mouth of the hole. Moist clay stemming is tamped into the drill hole, and then the brass tube is withdrawn.

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The tube and hole made therewith provides an outlet for escape of the evaporating oxygen until the shot has been fired; the wad above the cartridge prevents the moist clay from stopping up the tube in tamping. The escaping oxygen, if open lights are used, presents practically the only recognized danger leading to premature firing, but if there is no fire damp nor coal dust present, the risk of premature firing is no greater than in charging any other high explosive into a drill hole, and is less than in charging black blasting powder in the presence of open lights. On the other hand, use of oxygen explosive eliminates the great danger in digging out misfires or unexploded cartridges of dynamite or black blasting powder, as one needs merely to wait about 30 minutes after firing for the oxygen to evaporate.

The rate of evaporation of liquid oxygen is a most important factor in the use of the explosive. The carbonaceous material can be weighed, but the proper quantity of liquid oxygen must be ascertained by prior trials of the evaporation with the particular kind of cartridge used. It was decided in making the experiments that 10 minutes would ordinarily be required in practice for firing a group of two or three shots, therefore this was the length of time taken in calculating the ratio of oxygen to carbonaceous material.

COMPARATIVE STRENGTH TESTS AT PITTSBURGH STATION.

It was found, under the conditions of test involving use in 10 minutes after soaking the cartridge, that the strength of certain mixtures as measured in the ballistic pendulum exceeded the strength of 40 per cent straight nitroglycerin dynamite. The results of analyses and tests of three mixtures follow:

Comparison of samples of liquid oxygen explosive with dynamite.

SAMPLE A.

Analysis of sample:	Grams.
Crude oil	31.1
Kieselguhr	46.7
Cheesecloth	5.0
Corrugated pasteboard insulator	38.5
Liquid oxygen	161.1
Total	282.4

Length of cartridge, 14.0 cm. (5.6 inches).
Outside diameter of cartridge (pasteboard container), 5.7 cm. (2.3 inches).
Diameter of inner cartridge, 4.1 cm. (1.6 inches).
Depth of bore hole, 55 cm. (22 inches).
Measurement of swing of pendulum, 4.72 inches.
Unit swing of 40 per cent dynamite, 3.35 inches.
Unit deflective charge of liquid oxygen explosive, 200 grams.
Unit deflective charge of 40 per cent straight dynamite, 227 grams.

Comparison of samples of liquid oxygen explosive with dynamite—Continued.

SAMPLE B.

Analysis of sample:	Grams.
Crude oil	11.3
Kieselguhr	60.9
Lampblack	23.8
Cheesecloth	6.0
Corrugated pasteboard insulator	60.0
Liquid oxygen	184.0
Total	346.0

Length of cartridge, 18.0 cm. (7.1 inches).
Diameter of cartridge, 4.1 cm. (1.6 inches).
Diameter of insulated cartridge, 5.5 cm. (2.3 inches).
Unit deflective charge, 217 grams.

SAMPLE C.

Analysis of sample:	Grams.
Crude oil	10.1
Kieselguhr	54.2
Wood pulp	38.9
Cheesecloth	5.7
Corrugated pasteboard insulator	58.0
Liquid oxygen	149.1
Total	308.0

Length of cartridge, 21.5 cm. (8.5 inches).
Diameter of cartridge, 4.1 cm. (1.6 inches).
Unit deflective charge, 211 grams.

In the foregoing experiments each sample was fired by a No. 6 electric detonator.

It will be noted that the unit deflective charges of the liquid oxygen used in these tests were 200, 217, and 211 grams, respectively. The unit deflective charge of 40 per cent "straight" nitroglycerin dynamite is 227 grams. In other words, the strength of the liquid oxygen explosive was 4 to 12 per cent greater than 40 per cent nitroglycerin as indicated by this standard Bureau of Mines test. Practical tests in a stone quarry near Pittsburgh demonstrated that the work done was at least equivalent to that of 40 per cent dynamite.

The dipping container designed at the Pittsburgh station consisted of a double-wall brass cylinder open at the upper end, having the air evacuated from the space between the walls. To obtain as nearly as possible a complete vacuum, the Dewar method was adopted of placing charcoal in the evacuated space to absorb any residual air at low temperature. The container was of sufficient diameter to permit the soaking of four or five cartridges at the same time.

TESTS DEMONSTRATING IGNITION OF FIRE DAMP.

To determine whether it was safe to use liquid oxygen explosive in a gaseous coal mine, tests were made of firing the explosive in an atmosphere containing 4 per cent of methane and with coal dust present. Ignition of the gas and dust resulted, showing that the explosive should not be used in gaseous coal mines. Conclusive tests were not made of the result of firing into coal dust alone.

In tests of the rate of detonation of the explosive, one test showed 3,031 meters per second, and the other, 2,996 meters per second, as compared with 1,447 to 4,439 meters for permissible explosives. The ignition of gas and dust was evidently due to the greater duration of flame of the liquid oxygen explosive, which was found to be 7.125 milliseconds, as compared with 0.342 for an average permissible explosive, no permissible explosive exceeding a duration of 1 millisecond. The length of flame was 2½ times that of an average permissible explosive; this would also make ignition of gas and dust more likely to occur.

NEED IN THE UNITED STATES OF SMALL LIQUEFYING UNITS.

A feature that has not been satisfactorily worked out in this country is the development of a small liquid-oxygen manufacturing plant that could be installed without undue expense at a mine or a quarry. There was promise that such plants might be developed by American manufacturers, but the uncertainty of how much demand there might be for such apparatus and the difficulty of obtaining raw materials under war conditions prevented the production of such machinery. However, had the war continued, the increasing scarcity of nitroglycerin would probably have led to forcing the adoption of liquid oxygen explosives for certain uses, as was done in Germany.

EFFECT OF PURITY OF OXYGEN.

It was found, as in the later German tests, that a high percentage of oxygen rather than of liquid air was most important. This fact explains some discrepancies in the results of earlier German testing, when its importance was not appreciated. Comparative tests—the relative expansion caused by firing in the Trauzl lead blocks—were made with different percentages of liquid-oxygen and nitrogen with these results: With 33 per cent oxygen in the liquid air no explosion occurred; with 40 per cent oxygen present the enlargement of the bore hole was 9 c. c.; with 50 per cent oxygen, 80 c. c.; with 55 per cent oxygen, 147 c. c.; and with 98 per cent oxygen, 384 c. c. As regards other explosives, 40 per cent "straight" nitroglycerin dynamite gives an enlargement of 267 c. c., 50 per cent "straight" nitroglycerin dynamite, 281 c. c., and 60 per cent "straight" nitroglycerin dynamite, 321 c. c. Thus with 98 per cent liquid oxygen the enlargement was 20 per cent greater than with 60 per cent "straight" nitroglycerin dynamite.

At the testing station at Neubabelsberg, Germany, comparative figures obtained from tests in a Bichel gage show that the amount of liquid oxygen explosive required for a pressure of 40 kg. was as follows: With 50 per cent oxygen in the air, 115 grams; with 60 per cent oxygen, 103 grams; with 70 per cent oxygen, 96 grams; with 80 per cent oxygen, 87 grams. With 80 per cent purity of oxygen the oxyliquit "attains the strength of blasting gelatin."

In this connection it must be noted that nitrogen vaporizes or boils at a lower temperature than oxygen, and this fact forms the basis of the various liquefying apparatus. The boiling point of nitrogen is −195° C., and of oxygen, −183° C. Therefore the liquid on standing tends to free itself of nitrogen and the percentage of oxygen tends steadily to increase. Necessarily this is not an economical way of obtaining pure oxygen as some of the oxygen is evaporated with the nitrogen. Such serious loss is not experienced in a good liquid-oxygen making apparatus in which the thermal exchanges have been carefully arranged.

RECENT GERMAN DEVELOPMENT OF LIQUID OXYGEN EXPLOSIVES.

In the November 11, 1915, issue of Stahl und Eisen an article by Diedrichs[a] on the production and use of liquid air for blasting purposes describes the status of the developments in Germany at that time. The substance of this important review of German developments is given in the following abstract:

Early attempts to use liquid air explosives had failed, owing to the difficulty of manufacturing a suitable cartridge, and to the lack of experience in handling the explosive, despite the fact that the extraordinary explosive strength of liquid air suitably mixed with a carbon carrier had been demonstrated beyond doubt. Cartridges were well prepared but part of the liquid air had evaporated before being put into the drill hole. Then on insertion of the cartridge in the drill hole the natural rock heat gasified the liquid so rapidly that the stemming and even the cartridge itself were hurled out. Experiments were also made with closed metal cartridges filled with carbon elements and compressed oxygen. It had been tried further to use liquid air as an explosive by filling a closed metal cartridge without the admixture of a carbon carrier and by utilizing merely

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[a] Diedrichs, H., Die Erzeugung und Verwendung flüssiger Luft zu Sprengzwecken: Stahl und Eisen, Jahrg 35, 1915, pp. 1146–1151.

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the explosive force developed through gasification in consequence of the rock heat, but these attempts were unsuccessful.

Diedrichs states that about six or seven years ago (1912 to 1913) it occurred to mining engineer Kowatsch not to fill the cartridge with liquid air until it had been inserted in the drill hole. At about the same time mining assessor Schulenberg conceived the idea of applying the principle of the Dewar patent flask to increase the capacity of the cartridge for taking up liquid air, thus lengthening its life by cooling it to the temperature of the liquid air. The cooling and filling by immersion are done before charging the drill hole. Both methods have been successfully adopted in practice.

Liquid air used for blasting purposes is not the product commonly known under this name, but is more correctly designated as "liquid oxygen," for it contains 85 per cent oxygen. Still higher concentrations of the oxygen can be obtained by evaporating the liquid air at ordinary mine temperatures, as the nitrogen, owing to its lower boiling temperature, evaporates more rapidly than the oxygen. As the oxygen evaporates also, although in proportionately smaller amount, it is clear that such a procedure is wasteful of oxygen. The loss, however, is negligible when the so-called "rectification" process is used. This process permits producing liquid air with 95 and even 99 per cent oxygen, but for blasting purposes a concentration of 85 per cent is sufficient. At this oxygen content the liquid "air" has a specific gravity of 1.1 and a temperature of −185° C. In spite of this low temperature the liquid does not burn the human skin on lightly touching it, and there is small danger of one's hand being injured if the cold liquid is accidentally spilled on it. However, the possibility of painful burns through contact with the liquid air should not be underestimated, Diedrichs cautions, in the handling and charging of cartridges.

PRODUCTION OF LIQUID AIR.

The air liquefaction installations (figs. 1 and 2) furnished by the Sürth Machine Factory (Cologne)[a] are electrically driven, and includes an air compressor, solution pump, and ammonia compressor. The air is sucked through a purifier where it is freed from dust and carbon dioxide by means of a solution of caustic potash or soda. The solution is kept circulating by means of the small pump. The separator serves for separating out the solution carried along. The air then passes into a three-stage compressor. The pressure stage is

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[a] One German writer states: "The German society for the exploitation of the Linde patents is able to furnish installations giving an hourly output of 10 kilograms (23 pounds) of liquefied rectified oxygen." The price would be about 25 centimes (5 cents) per kilogram, including amortization and interest on capital invested.

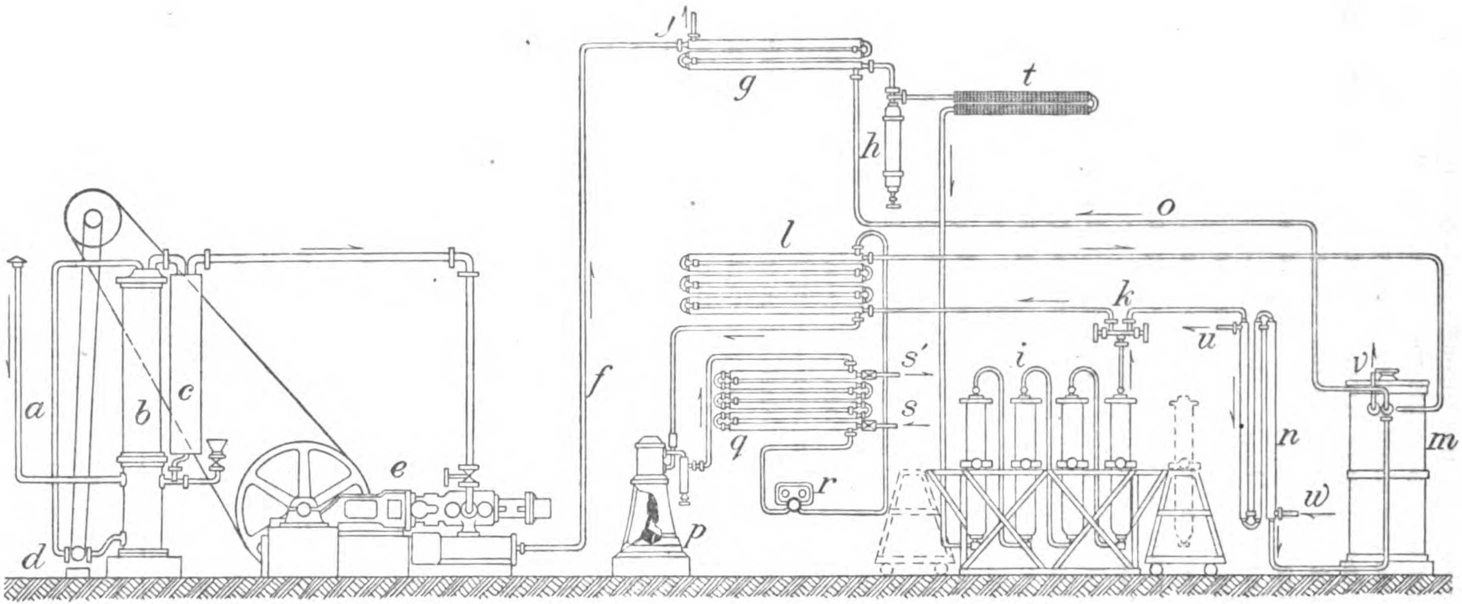

FIGURE 1.—Outline of air-compressor plant (after Diedrichs). *a*, Air inlet; *b*, purifier in which is circulated caustic-potash solution; *c*, separator; *d*, pump connection; *e*, three-stage compressor; *f*, high-pressure pipe; *g*, precooler; *h*, oil separator; *i*, drying battery (containing caustic potash or soda); *j*, nitrogen escape; *k*, three-way valve; *l*, cooler; *m*, liquefying apparatus; *n*, so-called "thawing" device, steam jacketed; *o*, cold-nitrogen pipe; *p*, ammonia or carbonic-acid compressor; *q*, condenser; *r*, regulator; *s*, *s'*, water connections for cooler (*q*) jacket; *t*, rewarming device; *u*, condensed water outlet for thawer; *v*, warm-air vent for liquefier; *w*, steam inlet to "thawer" *n*.

the same as in all cylinders. After each pressure stage the temperature of the compressed air is lowered by cooling coils to the initial temperature, so that the compressed air leaves the compressor with a temperature of 15 to 20° C. The air then passes through a high-pressure pipe into the precooler, where it is cooled by cold nitrogen escaping from the liquefaction apparatus. On leaving the preliminary cooler the air is freed from oil in an oil separator after having been heated again by the outside temperature; it then passes into a drier, where it is freed from moisture and from the last remnant of carbon dioxide by means of caustic potash or soda. After the air has thus been preliminarily cooled and purified it passes through a three-way valve into the cooler, where it is artificially cooled to —20° C. From the cooler the air passes into the liquefaction apparatus, where it is liquefied and separated into oxygen and nitrogen.

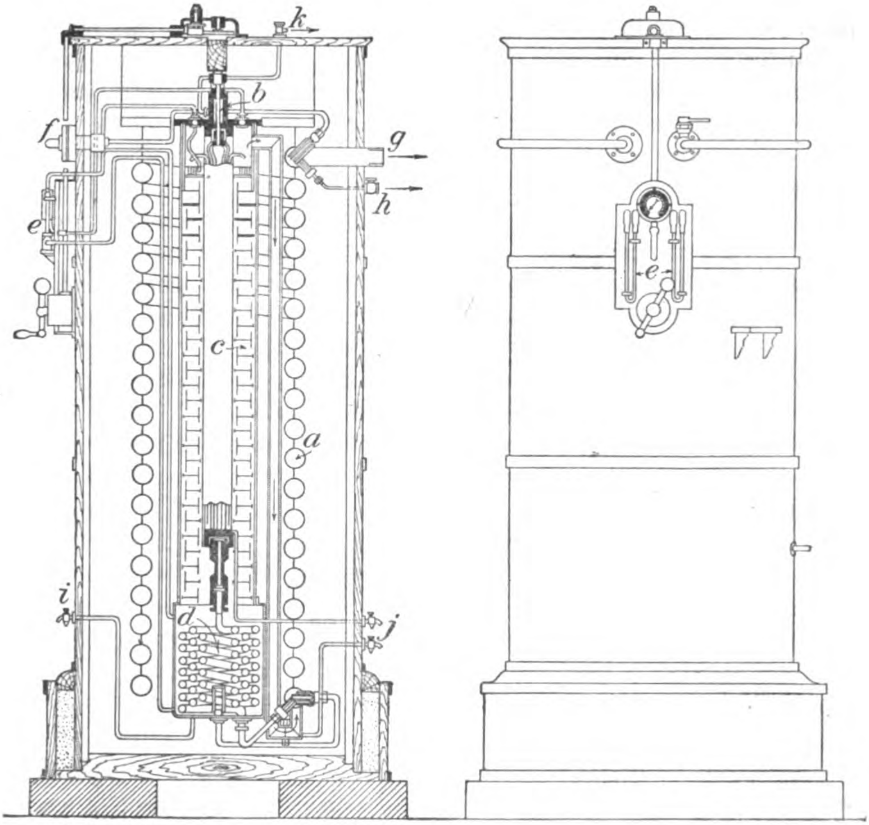

FIGURE 2.—Liquefying apparatus (after Diedrichs). *a*, Heat exchanger; *b*, regulator valve; *c*, rectifier column; *d*, compressed-air coils surrounded by liquid oxygen; *e*, fluid-depth gages; *f*, compressed-air inlet; *g*, nitrogen outlet; *h*, oxygen outlet; *i*, liquid oxygen tap; *j*, drain pipe; *k*, escape valve.

STORAGE OF LIQUID AIR.[a]

The vessels in which liquid air is kept must be perfectly insulated against the outside temperature in order to confine the evaporation of the liquid to a minimum. This important requirement is met only by a vacuum; for this reason, double-walled, highly insulated vessels are used for the storage and transportation of liquid air. Copper and brass so far seem to be the most suitable material for this purpose. Glass would be the ideal material, but, owing to its fragility, it hardly comes into consideration in practice and its use remains confined to laboratories. The bottles have one or several vacuum jackets. For the outer jackets steel may be used. For obvious reasons the shape of the container is almost exclusively oval or spherical.

Although the best and most efficacious metals are selected for the manufacture of the vessels, still there is no metal which in the long run does not allow the air to pass through. On the other hand, the requirements of the vacuum, in view of the economical storage of the liquid air, are too high to be met satisfactorily by the air pump alone. On this account the idea contained in the Dewar patent of 1905, is used for maintaining a more perfect vacuum.

Heated charcoal is placed in the space to be evacuated in the double wall of the container, evacuation is carried as far as possible with an air pump, and the connection is sealed. If the vessel is filled now with liquid air, then the coldness is transmitted through the wall to the charcoal, which sucks up the remaining air, and produces an almost perfect vacuum. By this procedure the required vacuum is generated anew at each filling of the container and is kept up as long as liquid air is present therein. The mouth of the container must not be entirely closed as the intense gasification of the liquid leads to high and very dangerous pressures within a tightly closed vessel. The evaporation losses in these bottles amount to only 4 to 6 per cent in 24 hours.

GERMAN TECHNIQUE IN USE OF LIQUID OXYGEN EXPLOSIVE.

The filling of the cartridges with liquid air, which is done at the place to be blasted, is effected in two ways. The method of Kowatsch and Baldus, Diedrichs states, is as follows:

A single cartridge of suitable length, consisting of a thick pasteboard shell filled with the carbon carrier, is placed in the drill hole and connected in the usual manner with fuse, or when electrically ignited, with the lead wires. The free space of the drill hole in front of the cartridge is filled with plastic stemming, such as clay. The cartridge[b] is equipped with two paper tubes which stick out of the drill hole; one tube reaching to the bottom of the cartridge is used for filling the latter with liquid air, and the other tube, which is shorter, serves as an outlet for the evaporating liquid air.

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[a] Abstracted from article by Diedrichs. See p. 16.

[b] Called "Kowastite."

During the tamping of the drill hole needles are inserted in these tubes through the stemming material, the needles being withdrawn after the stemming is in place. To fill the cartridge the inlet tube is connected through a flexible metallic hose with the charging vessel, and the latter is turned down. The overpressure arising in the vessel through evaporation drives the liquid air into the cartridge. The termination of the charging is indicated by the cessation of the hissing sound accompanying the escape of part of the liquid air from the drill hole in the form of vapor. Now the cartridge is ready for blasting, and the shot must be fired as rapidly as possible, as, owing to the steady gasification promoted by the rock heat, the explosive strength of the cartridge gradually decreases and is entirely lost after the complete gasification of the liquid air.

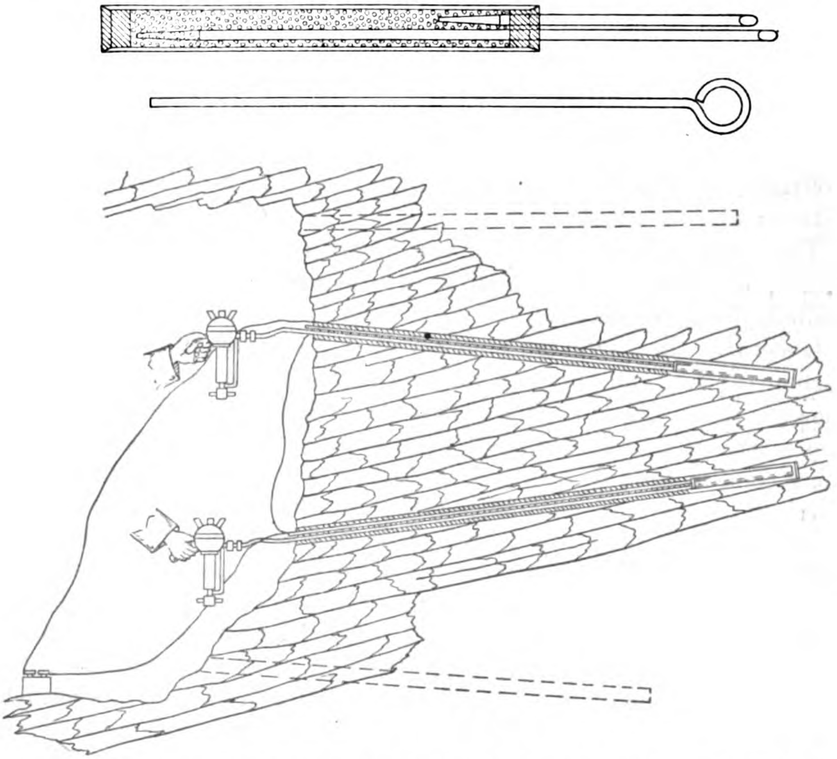

FIGURE 3.—Method used by Kowatsch and Baldus for placing cartridge in drill hole and impregnating it with liquid oxygen, (after Diedrichs).

Schulenberg's method differs from the first method in this, that the voids in the cartridge materials are filled with liquid air before the cartridge is put in the drill hole, by inserting it in a dipping or soaking container. Then the cartridge is placed in the drill hole, connected with fuse or with igniting wires, and the drill hole is filled with stemming. It is necessary during the tamping to insert a tube for carrying off the evaporated liquid air. During the execution of these operations the cartridge would have lost its explosive strength partly or entirely through gasification, so the paper shell is cooled by the cold oxygen gases to the temperature of the liquid prior to its being dipped in the liquid oxygen. The precooling renders the carbon carrier more capable of absorbing liquid air, and any excess of oxygen prolongs the life of the prepared cartridge. Precooling, however, is valuable and economical only when the gases escaping from the dipping container are used for the cooling of the cartridges, and in this manner the liquid air is most perfectly utilized without excessive loss.

The construction of the dipping apparatus is based on the same principle as the containers, that is to say, they are made double-walled, the space between the walls being devoid of air.

Generally the cartridge consists of a gauze bag filled with the carbon carrier, and this bag may be inclosed in a shell in order to increase the insulation. In contrast to the first method, in which only one cartridge of suitable length can be used, the cartridges used in the second method have a normal length of 250 to 300 mm. and the required number thereof is introduced into the drill hole.

Diedrichs, in referring to the tests conducted by Dr. Seider[a] in 1906, quotes him as saying "that in the tests made the cartridges were either filled with liquid air through paper tubes reaching to their bottom, or immersed entirely in the liquid air and left therein until they sucked themselves full." The gain in precooling the cartridge by the cold oxygen gases, Diedrichs says, is contained in Dewar's patent relating to the absorption of oxygen by cold carbon.

For the immersion method without precooling, Dr. Seider used cartridge shells consisting of two equally long tubes with double walls, open at one end and closed at the other. These tubes were shoved one into the other, thus forming a closed cartridge in which the liquid air evaporates but slowly. In general it may be said that the greater the diameter of the cartridge the smaller is the evaporation, and that it is advisable to work with drill holes of at least 30 mm. (1.2 inches) diameter. In this respect the conditions in ore mines and of rock work in coal mines are not particularly favorable, as the drill holes used in this work (in Germany) are only from 20 to 25 mm. (0.8 to 1 inch) diameter.

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[a] Seider, Ludwig, Oxyliquit: Ztschr. ges. Schiess.-und. Sprengstoffwesen, vol. 1, 1906, p. 87.

COMPARISON OF THE TWO METHODS OF USE.

Diedrichs, in reviewing these two methods, which are advocated by the same company—the "Sprengluft Gesellschaft" of Essen—remarks that both have their advantages and disadvantages. The first method (Kowatsch and Baldus) has the advantage of the highest working safety owing to the fact that the cartridge is not explosive until it has been inserted into the drill hole. The disadvantages are of a manifold nature. In the first place it will hardly be possible in practice to use a "kowastite" cartridge of 1 meter length and more, as often required for blasting purposes in mining, because a single kowastite cartridge 0.5 meter in length is difficult to handle. The insertion into the bore hole of several small kowastite cartridges, one after another, is precluded by their construction and by the charging method. In the second place, with certain charging materials this method does not guarantee the proper composition of the explosive in the drill hole; it may happen that the mass is unevenly or imperfectly soaked with liquid air, and an excess of burning carbon is present which is blown out by the blast, or which burns only to carbon monoxide, giving rise to poisonous and combustible afterdamp, decreasing at any rate the explosive strength.

These disadvantages do not exist in the prior-immersion (Schulenberg's) method; it permits placing the required number of cartridges into drill holes of any depth, exactly as in the charging of dynamite cartridges, with which the miner is familiar, as well as the possibility of perfectly soaking the cartridges themselves. The disadvantage of the method is that despite the intense coldness of the cartridges, the time required for loading the drill holes makes it almost impossible to fire more than two shots simultaneously, or to fire shots in a place where much time is required for the shot firer to gain a safe place. For this reason all the recent attempts tend in the direction of prolonging the life of the cartridges. The complicated precooling and immersing may be regarded as a further disadvantage; but the filling of the cartridges in the drill hole, as is done in the first method, is not a very simple matter either, and requires about the same amount of time.

The danger that during the ignition an excess of carbon burns only to carbon monoxide exists in both methods when the shot is not fired in due time and the liquid air is reduced by evaporation to a smaller amount than is required for the perfect combustion to carbon dioxide. If the ignition takes place with a sufficient amount of oxygen, then there is perfect combustion to carbon dioxide, and a disagreeable or even noxious afterdamp does not occur, so that the blasting place may be approached immediately after the shot. The timely firing of the shot is therefore of the greatest importance, not only in view of the afterdamp, but also in view of the blasting effect. This consideration restricts the number of the simultaneous shots, a disadvantage which ought to be partly compensated for, Diedrichs thinks, by the greater blasting strength of liquid air explosive. At any rate the aforementioned circumstances sets certain bounds to the liquid air method, such as in shaft sinking.

With regard to the afterdamp, Diedrichs points out that in ore mines containing iron sulphide there occurs sometimes an afterdamp which irritates the breathing organs, and in some places there occur odors which most probably are due to an incipient roasting of the sulphide ores. (This is probably true for the use of any explosive, but the amount of such gases would seem to be insignificant.)

Which of the two methods is preferable will have to be learned from practice. Local conditions and particular circumstances will probably also come into play.

The liquid air blasting method is beset with a great drawback; according to the tests made heretofore, Diedrichs says, the liquid air explosive has not proved to be safe against fire damp. Endeavor is being made to remove this great defect by means of a particular composition of the cartridge charge, and it is claimed that success has been attained very recently.

Diedrichs comments that admixtures of graphite and common salt, used for this purpose, enhance the immediate fire-damp proofness, as graphite owing to its great absorption of heat lowers the high temperature during the ignition, and the common salt, on decomposing, deadens the flame; but combustible gases are evolved which are ignited by the shot itself. In addition to this, the admixtures, as in other safety explosives, weaken the effect of the explosive, because the admixtures do not suck up the liquid air, but decrease the charge density of the cartridge. One can obtain an explosive of higher or lower brisance by means of suitable admixtures, and by the proper selection of the filling materials with a particular absorption capacity. These filling materials absorb a quantity of liquid air equal to three or four times their own weight. It has been found, however, that in order to start the combustion it is useful to add a liquid hydrocarbon (petroleum, benzine, benzol, oil, naphthalene, solvent naphtha, paraffin, etc.); the hydrocarbon is absolutely necessary in conjunction with kieselguhr, as this material is not a carbon carrier, but serves merely as an absorbent.

The ignition can be equally well effected electrically, with black powder fuses, with fulminate caps and fuse, or with fuse alone. The most reliable, however, is the ignition with cap and fuse.

GERMAN ESTIMATES OF COST IN USE OF LIQUID OXYGEN EXPLOSIVE.

According to the results of the blasting tests in various mines, which have been published so far, the economy must be regarded as highly favorable. However, as these data are general, they must be examined with some care, the more so in dealing with so-called "spectacular tests" and not with the result of actual mine work. These trials give the following average result:

One kilogram of marsite (a liquid oxygen explosive) has the same effect as 2.2 kilograms of gelatin dynamite, 6 kilograms of black powder, 3 kilograms of cheddite. These, of course, are unusually favorable results.

The cost of manufacturing 1 liter (0.946 quart, U. S. liquid measuse) of liquid air,[a] including interest and amortization, is 24 pfennig (6 cents, prewar exchange value); the assumption is a plant with an hourly production of 20 liters—that is, a plant of medium size running 12 hours a day—and spending for electric power 3 pfennig (0.7 cent) per kilowatt-hour. Diedrichs remarks that in shop bills the cost of manufacture is given as 15 to 18 pfennig (3.6 to 4.3 cents); this figure, however, is too low.

Take as an example a mine with a yearly consumption of 40,000 kilogram (88,000 pounds of dynamite, which corresponds to a yearly output of about 400,000 metric tons (of 2,205 pounds) of coal. If, for safety's sake, the ratio of the blasting strength of liquid air explosive to that of dynamite is taken as 1.5:1, then 26,700 kilograms (58,700 pounds) of liquid air is required yearly. The liquid air cartridge at the moment of ignition must contain one-third of its weight of carbon filling material and two-thirds of liquid air. Hence 26,700 kilograms of liquid air explosive contains 8,900 kilograms of filling material and 17,800 kilograms or 16,200 liters of liquid air. In order to make the amount of liquid air available at the moment of blasting, about 72,000 liters (25,000 gallons U. S. liquid measure) must be produced in view of the evaporation losses during transportation and especially during the loading.

Assuming 300 working days of 12 hours each, one gets—

$$\frac{772{,}000}{300\times 12}=20 \text{ liters per hour.}$$

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[a] Liquid air containing over 90 per cent oxygen, one liter weighing approximately 1.1 kg. (2.4 lbs.).

Hence the calculation may be based on the cost of manufacture of a 20-liter plant. The yearly costs are calculated by Diedrichs as follows:

Yearly cost of a 20-liter plant (by Diedrichs).

	Marks.	Dollars.[a]
72,000 liters of liquid air at 24 pfennigs (6 cents)	17,280	4,320
8.900 kilograms of filling material at 35 pfennigs (9 cents)	3,115	779
178.000 cartridge shells at 3 pfennigs (0.75 cent)	5,340	1,335
[200 mm. long and 35 mm. diameter (8 inches by 14 inches); weight of filling material 50 grams (1.8 ounces).]		
Wages for filling the cartridges with liquid air at 2 pfennigs (0.5 cent)	3,560	890
License tax at 1 pfennig (0.25 cent) per ton of coal extracted	4,000	1,000
Total for 26.700 kilograms (58,700 pounds) of liquid air explosive	33,295	8,324
Total for 40,000 kilograms (88,000 pounds) of dynamite	56,000	14,000
Saving per year	22,705	5,676

Unit costs (derived from above table and interpolated by author).

1 kilogram (2.2 pounds) of liquid oxygen explosive	1.25	0.31
1 pound of liquid oxygen explosive	----	.14
1 kilogram of dynamite costs	1.40	.35
1 pound of dynamite costs	----	.16
1 kilogram (2.2 pounds) of dynamite produces 10 metric tons of coal.		
1 pound of dynamite produces 4.5 metric tons of coal.		
1 kilogram (2.2 pounds) of liquid oxygen explosive will produce 15 tons of coal (estimated).		
1 pound of liquid oxygen explosive will produce 6.8 tons of coal (estimated).		
Cost of dynamite per metric ton (2,205 pounds) of coal	0.14	3.5
Cost of liquid oxygen explosive per metric ton (2,205 pounds) of coal	.083	2.1

The remaining expenses, such as cost of fuse, blasting caps, loading the drill hole, are the same in both blasting methods, and the cost of transportation to the blasting place is also the same, so that they may be left out of the calculation. In spite of the partly unfavorable assumptions for the liquid air explosive, a not insignificant saving is being realized.

As a further illustration of the economy realized a few more figures are presented by Diedrichs relating to the working results of two months (1915). The cost of liquid air explosives for 1 ton of coal (2,205 pounds), the amortization and interest being 15 per cent for the machines, and 33⅓ per cent for the containers, is as follows:

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[a] Prewar exchange value.

Cost of liquid "air" explosives per ton of coal produced.

	At present.		Formerly.	
	Pfennigs.	Cents.	Pfennigs.	Cents.
Giesche mine	7.71	1.93	12.7	3.2
Brandenberg mine	5.64	1.41	10.8	2.7
Antonien mine	7.5	1.87	13.5	3.4

Cost of production of liquid "air" in a plant with an hourly production of 20 liters (Germany, 1915).

COST OF ERECTION.

	Marks.	Dollars.
Cost of machinery, including 500 marks for spare machines	33,000	8,250
Cost of electric plant	4,200	1,050
Cost of immersion and cooling vessels	8,300	2,075
Cost of building and foundations	6,000	1,500
	51,500	12,875
Yearly interest and amortization:		
12 per cent of 37,200 marks (11 years)	4,464	1,116
30 per cent of 8,300 marks (about 3½ years)	2,490	622
7 per cent of 6,000 marks (25 years)	420	105
	7,374	1,843

COST OF PRODUCTION PER LITER.

[Yearly production (300 working days of 12 hours each), 72,000 liters.]

	Pfennigs.	Cents.
Interest and amortization, $\frac{737{,}400}{72{,}000}$	10.24	2.56
Wages $\frac{180{,}000}{72{,}000}$	2.5	.62
Oil	1.0	.25
Chemicals	1.0	.25
Cooling water, 5 cubic meters per hour (0.25 cubic meter per liter) at 5 pfennigs per cubic meter	1.25	.31
Cost of repair, 500 marks. 50,000÷72,000	.7	.18
Current, 2.4 kilowatts per liter, at 3 pfennigs per kilowatt	7.2	1.80
Total	23.89	5.97
Production cost is, approximately, per liter	24	6
Production cost is, approximately, per gallon		23

DIEDRICHS' COMPARISON OF LIQUID OXYGEN EXPLOSIVE METHODS.

A summary of the advantages and disadvantages of the liquid air blasting method in comparison with the dynamite blasting method is as follows:

Advantages:

1. Lower cost.
2. Elimination of the explosion danger during transportation and storage.

Advantages—Continued.

3. Favorable afterdamp.
4. Cartridges which may fall into the coal, and from thence into the washery, coking plant, or furnace can not explode.
5. The possibility of recovering cheap, pure oxygen gas for technical purposes as a by-product.

Disadvantages:

1. Owing to the rapid evaporation, the drill hole has to be loaded rapidly and skillfully, which requires a specially trained personnel.
2. For the same reason fewer shots can be fired simultaneously.
3. It is not possible to prepare large amounts of liquid air (as in a manufactory for wide distribution). The liquefaction plant must be at the blasting place or in the vicinity.
4. At present, at least, the procedure is not yet firedamp proof.

Diedrichs concludes that the status of the method is as follows: A number of mines, particularly in the Upper Silesian district (generally nongaseous) have already adopted this method; others are busy erecting such plants, driven by necessity, of course. Whether this method will stay after the restoration of settled conditions, will depend on the solution of the problem of fire-damp proofness and on the experience gained in practice; ultimately the continuance of this method will depend on the cost, as there is no doubt that the technical difficulties will be removed.

According to an unsigned foreign communication which was recently (1919) brought to the attention of the author, "the principal company manufacturing oxyliquit, the Sprengluft Gesellschaft, m. b. H., of Berlin, claims to have delivered each year an equivalent of 10,000 tons of nitric explosives. Even allowing for probable exaggeration, that shows how widely this product is used in Germany."

EUROPEAN OBSERVATIONS OF BUREAU REPRESENTATIVES.

Following the armistice, it was determined by the Secretary of the Interior, Franklin K. Lane, and the Director of the Bureau of Mines, Van. H. Manning, to send a committee of Bureau of Mines engineers and metallurgists to study the mining and metallurgical situation and such special developments as came about through the emergencies of the war. One of these investigations was the development in the technique and use of liquid oxygen explosive.

It was found that little progress had been made in the countries of the Allies of the United States, but there had been material advance made in the technique by the Germans as shown by installations

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at iron mines in Lorraine[a] and from information obtained from German technical papers.

However, no new principles were uncovered. The uneven development in application between the Allies of the United States as compared with the Germans, was because the former could import explosives ingredients, whereas Germany was thrown on its own resources as the stocks of Chilean nitrates and glycerin became exhausted.

Liquid oxygen explosive was not used either in Great Britain or France during the war, except that Claude, of France, inventor of the Claude liquefying process, had on one or more occasions gone up in an aeroplane to demonstrate the possibility of its use in a military way by dropping liquid oxygen bombs on the enemy. It was reported that the bombs operated successfully.

The bureau committee on visiting the Longwy steel plants, systematically destroyed by the enemy, found that the Germans had erected a Linde liquefying plant and had made the liquid oxygen explosives used for blowing up the machinery. Adjacent to the liquid oxygen machine in the Longwy plant there was an inclosure for storage of the cartridges, fuses, and detonators. These cartridges are made of strong paper wrapped three times, the cartridge having been formed on a split, round, wood stick, wedge-shaped for withdrawal after being filled; the outer edge of the paper and the bottom end of the cartridge is pasted or glued together; the paper at the top end, after filling with soot or other carbonaceous material, is merely folded down. The paper cartridges were marked "Sprengluft No. 100, 30×300 mm." (1.2 inches by 12 inches).

In this depository there were found small blocks of picric-acid explosive, about 2½ inches wide, 4 inches long, and 1½ inches thick, having a hole for inserting a detonator. Evidently these blocks were for destructive purposes where the charge was not confined, the liquid-oxygen explosive cartridges evidently being used where holes had been drilled in the machinery or foundations. There were fuses at hand; on the end of each was fastened what appeared to be large detonators with pointed ends, apparently filled with cork charcoal. These detonators seemed to be prepared for liquid oxygen soaking.

There was also a crude dipping vessel and a standard carrying container—a 5-liter spherical flask, air evacuated, the flask being placed in a strong galvanized-iron can. These were similar to that found at iron-mining plants. There was a yoke for the shoulders of a man, with chains and hooks for carrying two containers, hung on either end, to the point of use.

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[a] At the time of the visit—during the armistice—it was not possible to enter Germany except for military reasons. Therefore, the investigations had to be confined to the territory occupied by the Allies on the left (west) bank of the Rhine, including the Saar district.

The fuse was probably used in connection with the liquid oxygen detonators for firing the cartridges of liquid oxygen explosive. An assemblage of these several items is shown in the accompanying photograph. (Pl. I, *A*.)

The fuse, which is shown in better detail in the upper part of the photograph reproduced as Plate I, *B*, is a black-powder fuse with two wrappings of cloth and a synthetic rubber covering. Over this is a loosely woven fabric, seemingly as protection from abrasion. The wrappings of the fuse are not incombustible. The fuse burns by combustion through the central thread of black powder. The same type of fuse was seen in use in the Moyeuvre iron mine. Apparently the supposed necessity for the fuse having an incombustible coating mentioned by earlier German writers, was not found to be essential for safety from premature ignition by an open flame.

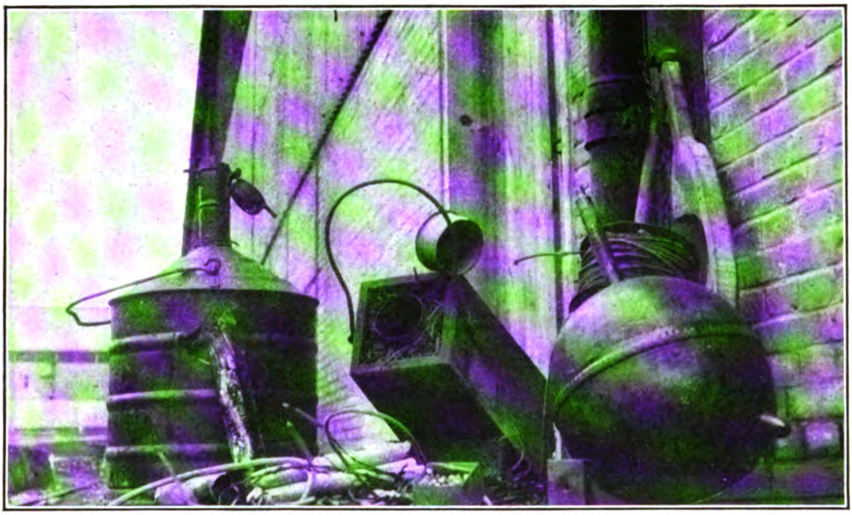
LIQUID OXYGEN INSTALLATION AT THE AUBOUÉ MINE, LORRAINE.

At the Auboué iron mine, in the Briey district, apparatus for making liquid oxygen explosive had been installed by the Germans when they took possession of French Lorraine. The machinery had been manufactured in Cologne, Germany, bearing the name Sürth-G. M. B. H., Sürth bei Köln. The liquefying process is a modification of the Linde system. Briefly the system is as follows:

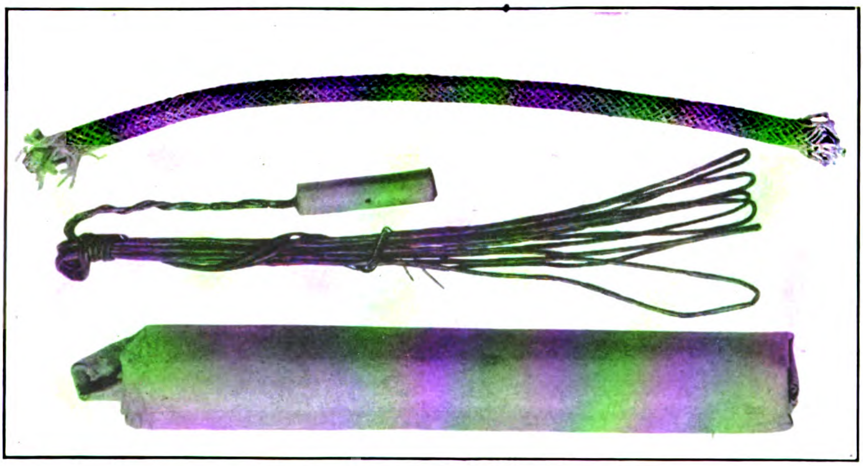
1. The intake air is first scrubbed in outside towers to get rid (by alkali treatment) of all traces of CO_2, to prevent freezing in the expansion valve.
2. The air then passes through a precooler, an ordinary ammonia plant, to get rid of moisture.
3. The air next passes through a three-stage compressor; the first-stage compression being 6 kg. per square cm.; the second-stage compression, 30 kg. per square cm., and the third compression, 200 kg. per square cm. (equivalent to 200 atmospheres, or to 3,000 pounds per square inch).
4. The air passes into and through a Linde liquefier, water cooling between steps.

The plant is driven by an 80-horsepower motor, and its capacity is 20 liters per hour when running well. The power consumption per liter is 1.9 kw.-hours. The carrying flasks in this plant hold 10 liters, and are in wood boxes with carrying handles. Larger flasks were tried but proved too heavy. The evaporation loss was 20 per cent in 6 hours. The filling material used was soot.

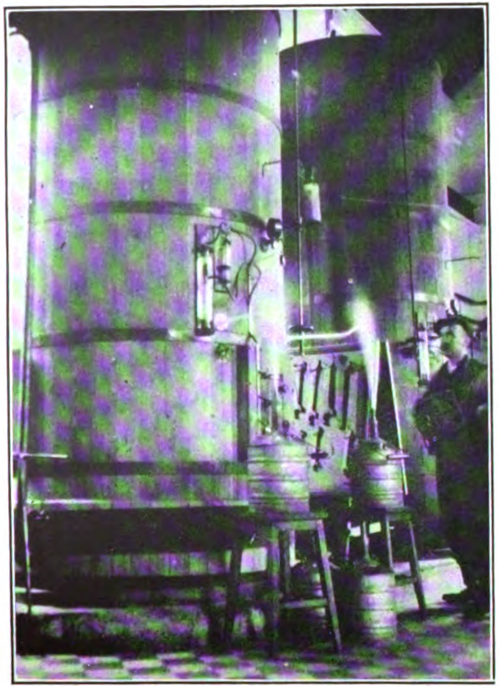
The dipping container is about 4 inches in diameter and 16 inches high with double walls. The container is placed in a larger vessel of metal with some insulating or packing material that is used more for protection than for insulation. The outer vessel rests on three



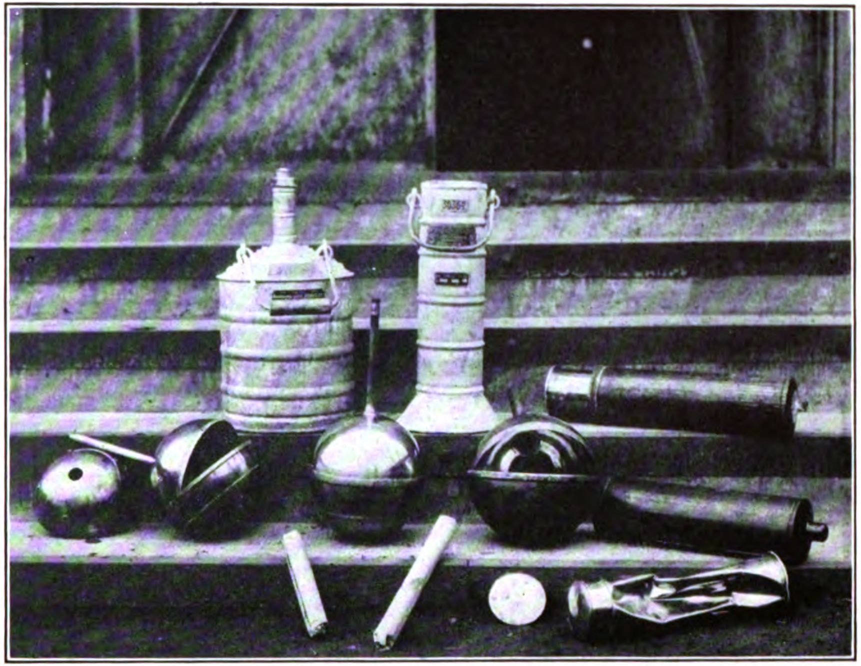
A. LIQUID OXYGEN APPARATUS FOR DESTRUCTIVE PURPOSES, LONGWY STEEL WORKS.



B. ELECTRIC IGNITER FOR LIQUID OXYGEN EXPLOSIVE.



A. LIQUID OXYGEN PLANT, MOYEUVRE IRON MINE.



B. CONTAINERS AND OTHER APPARATUS USED IN CHARGING CARTRIDGES OF LIQUID OXYGEN EXPLOSIVE, MOYEUVRE MINE.

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legs, with a little projection below—the connection for evacuating the space between the walls. At this mine the explosive was reported to be used with success. It is similar in effect to black blasting powder, but is more brisant.

INSTALLATION AT MOYEUVRE IRON MINE, LORRAINE ANNEX.

The Moyeuvre iron mine in annexed Lorraine (former German Lorraine), was owned by a French company, DeWendell & Cie. When the Germans took charge of the mine they installed a plant for liquid oxygen explosive which is now being used very successfully by the French. The oxygen-liquefying machinery, of the same character as that at the Auboué mine, was installed in 1916. It is driven by a 300-horsepower motor, but only 220 horsepower needs to be used. The capacity of the machine is 75 liters per hour. A photograph of this installation is shown in Plate II, *A*.

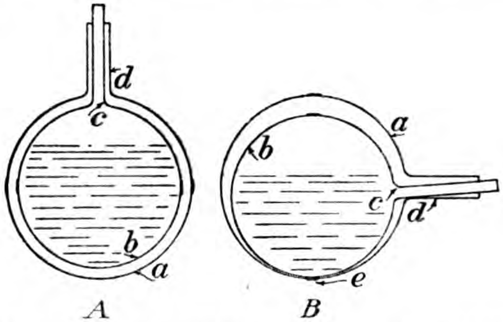

FIGURE 4.—Container for liquid oxygen. *A*, Container erect; *B*, container on side. *a*, Outer wall; *b*, inner wall; *c*, neck of inner bottle; *d*, neck of outer bottle. In *B*, *d*, and *e* show contact points of inner with outer bottle when container is on side. (By courtesy of Compressed Air Magazine.)

CARRYING CONTAINER FOR LIQUID OXYGEN.

The procedure in this mine is to furnish each pair of miners working in a room with a 5-liter container of liquid oxygen. The container and other apparatus used in charging the cartridges are shown in Plate II, *B*.

The vessel for the oxygen is a spherical flask of thin molded brass made in two parts, soldered, the inner flask being 222 mm. in diameter (8.8 inches) and the outer wall having a diameter of 238 mm. (9.3 inches). Between the walls there is a charcoal receptacle for absorbing residual air, as previously described. The flask has a long slender neck continuing the double evacuated space. According to a German description, this form of neck is to lessen evaporation. "This slender neck would make decanting difficult, as the air which must take the place of the outflowing liquid can not come in at the same rate of the liquid coming out. Therefore the neck of the inner bottle *b* (see fig. 4) which does not touch the external wall *a*, has been elongated; when the bottle is tilted, the interior tube, long and with thin walls, is bent; the inner bottle touches the outer at *d* and *e*, (see *B*, fig. 4) the insulation is interrupted; there is a warming up of

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the space, and the warmed up liquid—partly evaporized—creates an interior pressure which drives the liquid through the thin neck. It is thus possible to pour out quickly and steadily."[a]

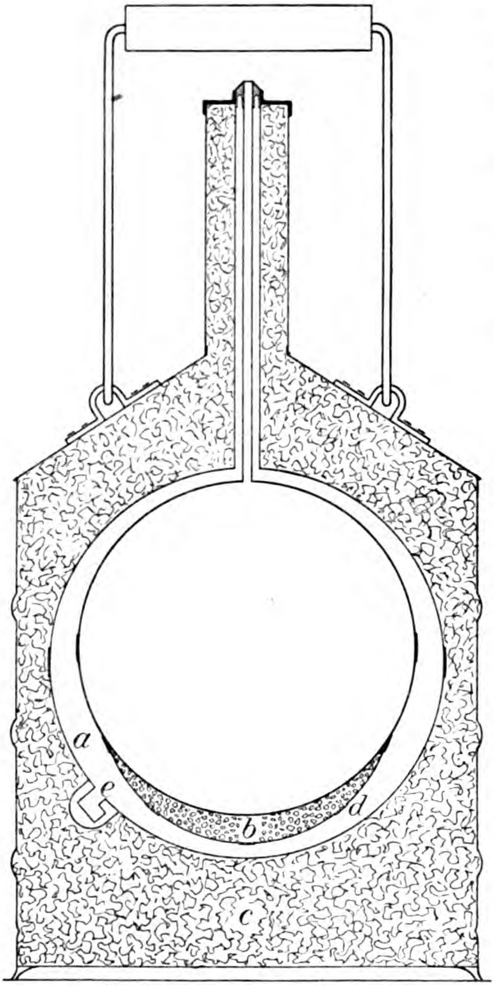

FIGURE 5.—Longitudinal section of carrying container. *a*, Evacuated space; *b*, charcoal; *c*, insulation; *d*, screen opening; *e*, attachment through which air is exhausted in producing vacuum. Prepared from photographs and sketches, not a construction drawing.

A section of the carrying container is shown in figure 5 and the various parts in Plate II, *B*. The evaporation loss from this container is very small, said to be 4 per cent per hour of the original content. The evacuation of the double walls lasts only about a year, according to the local mine management.

The purity of the liquid oxygen obtained is 95 to 98 per cent.

Paper cartridges are made in the mine shop, being formed on a split piece of round wood. Tough wrapping paper is used and when made up the wrappings provide four thicknesses. This company does not paste the paper edges together, as had been done in the cartridges that were found at the Longwy steel plant and at the Nuenkirchen testing station in the Saar district. The carbonaceous material used at this mine is abraided wood—that is, small wood fragments and splinters coarser than ordinary sawdust, the object of the coarser material being to lessen the brisance or quickness of the explosive action. The cartridges used at this mine are about 1½ inches in external diameter and 9 inches in length.

The cartridges are soaked in liquid oxygen for 15 minutes and they can be used up to 15 minutes from the time of taking out of the dipping vessel. No detonator is used, but a fuse of the character previously described.

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[a] News item, Liquid oxygen explosives: Compressed Air Mag., vol. 24, January 1919, p. 8998.

The dipping vessel holds four cartridges, the cartridge weighing before dipping 100 grams and afterwards 300 grams. The 5-liter carrying can which is furnished for one mining chamber in which two miners and one or two loaders work, contains liquid oxygen enough for making up 12 or 13 cartridges.

The miners work 8 hours and the 5 liters is enough for evaporation loss and for the shots fired. Often a can contains one or two liters when it is returned to the station for refilling. The rate of evaporation of the container at this mine is said to be only 50 grams per hour (1 per cent of the original content). The small dipping containers have evacuated walls, but the rate of evaporation is much higher, 150 grams per hour.

Soot was tried as carbonaceous material, but more poisonous gas resulted than from wood. The wood particles used are made by a special machine.

In this mine the holes were drilled in the ore by a rotating auger hammer drill driven by compressed air. The mine chambers are 7 to 13 feet high, the ore lying level. The roof is strong and requires little timber so that blasting can be done freely. The ore does not have many strongly marked faces, is dense and strong, but shoots easily. Formerly black blasting powder was used for blasting. After a miner has drilled one or two holes, they are charged and fired. The ventilation of the mine is by fans, and the air was good. The liquid oxygen explosive apparently yielded such inappreciable amounts of carbon monoxide, or other dangerous gases, that the men returned immediately

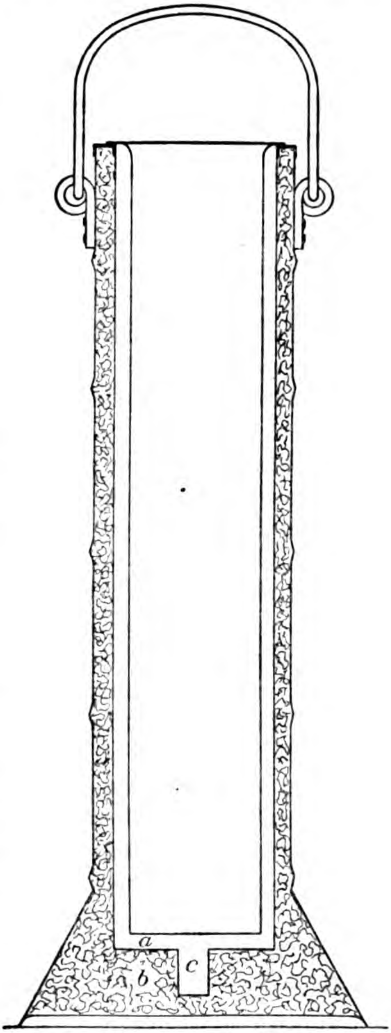

FIGURE 6.—Dipping vessel. Prepared from photographs and sketches, not a construction drawing. *a*, Evacuated space; *b*, insulation; *c*, attachment for evacuating space.

to the face after the shot had been fired. The smoke was light and caused no discomfort. The following details of blasting were noted.

EXAMPLES OF BLASTING AT MOYEUVRE MINE.

The miner, having taken the cartridge from the dipping container[a] in which he had placed the fuse, went to the face. At 10.12 a. m. he started loading the hole. The cartridge was pushed to the back of a 4½-foot hole, then a paper dummy containing loose fine ore was shoved lightly into the hole, the fuse being held by one hand and the dummy barely touching the cartridge; then other dummies with ore filling were inserted and rammed home tightly with a wood tamping bar. The object of not ramming the first tamping tight against the cartridge was to provide space for the liquid oxygen vapor to expand without blowing out the stemming. At 10:15 a. m. a fuse was lighted from a miner's open light and the miner and others retired to a safe distance. At 10.17½ a. m. the shot was fired, sounding like an ordinary dynamite shot, and the miners immediately returned to the face.

At another face a cartridge was inserted in the hole, 10.49 a. m.; then stemming was put in; at 10:51 the fuse was lighted; and at 10.52½ the blast occurred.

In each of these blasts the shot did good work, about two tons of ore being thrown down by each shot. The first shot cut ahead or beyond the point of the hole about 30 cm. (12 inches).

The liquid oxygen at this mine was stated to cost 1 franc 23 centimes (25 cents, pre-war value) a liter; with cartridge material and fuse added, 1 franc 45 centimes (29 cents) a liter of oxygen. This is equivalent to about 14 cents per pound of complete explosive. If the mine were working enough to keep the plant going continuously, the management claimed the cost of the oxygen would be reduced to 50 or 60 centimes[b] a liter, and that of the explosive to 70 or 80 centimes a liter. Miners are charged only 25 centimes for the explosive. The so-called No. 1 cartridge has the same effect as black blasting powder. One can make the explosive brisant or shattering, like dynamite, by using carbonaceous material more finely divided.

MOYEUVRE LIQUEFYING MACHINE INSTALLATION.

As regards the reliability of the liquefying machine, the producing apparatus is said to have run one year without stopping, but to have had six or seven stops since by breakage of the copper tubing.

The liquid oxygen is made at night, 6 p. m. to 6 a. m., but the mine works only one shift a day. The management stated that if the mine worked two shifts the plant would run 24 hours, giving more economical production.

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[a] Located 30 or 40 yards from the face.

[b] Prewar exchange 1 cent=5 centimes.

The liquid oxygen is stored in a big reservoir in the liquefying plant and the claim was made that it will stand with practically no loss for 24 hours. The plant cost 30,000 marks ($7,500, pre-war value).

LIQUID OXYGEN EXPLOSIVES TESTING AT SAAR STATION.

In the testing station at Nuenkirchen in the Saar district, which was kept going during the war but apparently not on research matters, were found samples of cartridges for liquid oxygen impregnation awaiting tests.

The director of the station stated that the use of liquid oxygen explosives had been forbidden in coking-coal mines, but had been permitted in some of the other coal mines where there was less danger of gas ignition. The carbon carrier was subject to great variation. The station officials had made tests with cork dust and with fine coal dust, also wood powder and coal dust, each in combination with liquid oxygen. The finer the material the faster is the rate of detonation. To decrease the danger of igniting gas or dust certain salts, such as rock salt, were to be tried as flame-cooling ingredients.

Liquid oxygen electric igniters or detonators made at Dortmund had been tested at the station. These detonators are made in a small pasteboard container, shaped something like a thick firecracker (shown in the middle part of Plate I, *B*) and contain an electric bridge with paper-insulated iron-wire legs. The combustible material consists of cork dust and oils. There are small holes in the pasteboard container to permit entrance of the liquid oxygen when immersed either previously or after placing in the cartridge (shown in the lower part of Plate I, *B*).

SUMMARY AND CONCLUSIONS REGARDING LIQUID OXYGEN EXPLOSIVES.

The development of liquid oxygen explosives since the time a mixture of liquid oxygen and carbonaceous material was first found, in 1897, to be explosive when ignited or detonated, was very slow until the great war began. Then Germany's Chilean nitrate imports having been cut off, its synthetically-manufactured nitrates being needed first of all for military explosives, attention was turned to the utilization of liquid oxygen explosive ("oxyliquit"), the raw materials for which are unlimited.

The principal reasons for slow development heretofore are as follows:

1. The use of liquid oxygen explosive virtually requires the installation of a local liquid air plant, involving a considerable first cost.

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2. The explosive is not suitable for use in driving tunnels, sinking shafts, and extensive stoping where a large number of shots must be fired at one time, because the charge must be fired within 10 or 15 minutes after dipping.

3. Liquid oxygen explosive can not be used in gaseous coal mines on account of its igniting firedamp.

4. Arranging practical methods of use in the ordinary mine or quarry is difficult because the miners or quarrymen have been accustomed all their lives to using dynamite or black powder.

Under the stress of necessity the development in Germany, after the beginning of the war, was rapid. As stated in these pages, liquid air explosive was used in large amounts in the Upper Silesian coal mines, which were nongaseous, in tunnel work, in subway and excavation work in cities, in iron mining—not only in Germany, but also in the French iron mines of Lorraine, which had been seized by Germany—and also for destroying French steel plants.

French officials in the Briey iron district believed that the explosive introduced by the Germans had come to stay.

The German military authorities evidently had confidence in this explosive, as a German confidential military paper was found entitled "Instructions for Blasting with Liquid Air—Staff of the 1st Royal Prussian Pioneer School." A translation of these instructions is given at the end of this paper (pp. 38 to 44).

The allied countries had not taken up the use of liquid oxygen, but this was in part due to a lack of knowledge of technique, which is slow in developing, and also because they were able to continue to import Chilean nitrate. However, had the war continued it is probable that, in America at least, the use of liquid oxygen explosive for mining purposes would have been compelled by the growing shortage of glycerin and nitrates as well as by the rapid increase in the cost of dynamite and black powder.

Now that the necessities of war are over the introduction of the method will have to depend on its own merits and on commercial conditions.

ADVANTAGES AND DISADVANTAGES OF LIQUID OXYGEN IN COMPARISON WITH DYNAMITE AND BLACK BLASTING POWDER.

ADVANTAGES.

The advantages of using liquid oxygen, as compared with the use of dynamite and black blasting powder, are as follows:

1. Lower cost per unit of material blasted.
2. No danger in transportation of explosives to point of use.
3. Practically no danger of premature ignition.

4. Elimination of the danger of misfires by waiting 30 or 40 minutes after lighting the fuse, when practically all the oxygen will have evaporated.

5. Elimination of the danger of unexploded sticks in mucking, or in the ore or coal going out of the mine.

6. No danger such as is experienced in handling and thawing frozen dynamite.

7. No danger from storage in magazines, as with dynamite and black powder, from lightning, or fire, or miscellaneous ignition.

8. Having a liquid oxygen installation to supply oxygen for special purposes, such as self-contained breathing apparatus and the oxy-acetylene torch.

DISADVANTAGES.

The disadvantages are—

1. The liquid oxygen because of its rapid evaporation must be used quickly and at a definite time after charging the hole, thus limiting the number of shots that can be fired in any one place to three or four, and making the firing of a group of shots more difficult although this can be done.

2. The practical necessity of having a liquefying plant near the mine to insure a supply.

3. To obtain the liquid oxygen at low cost the plant must be kept running regularly. That is, it is not suitable for intermittent work.

4. On account of igniting firedamp, liquid oxygen explosive can not be used in gaseous coal mines.

In spite of the disadvantages, the writer is of the opinion that the method has great merit and possibilities for lessening blasting costs in certain classes of mining, as in (1) coal mines which at present use black powder or dynamite, are free from fire damp, and do not produce dust of an especially dangerous character; (2) nongaseous anthracite mines; (3) iron, salt, and other mineral mines using a chamber method of mining where only a few shots are fired at one time; (4) quarries where a few large shots could be fired at one time. The liquid oxygen could be placed in a special container, and owing to the large quantity of liquid used in a single cartridge there would probably be small evaporative loss.

The chief cost of the liquid oxygen explosive being in the cost of the oxygen, there is hope of a decided reduction in cost through promised improvement in liquifying machines.

There has been a gradual increase in the cost of production of the standard explosives, which increases the amount of saving which might be effected through the use of liquid oxygen explosives to an extent that will tend to overcome the natural opposition of miners and quarrymen who have used the other explosives all their lives.

GERMAN MILITARY INSTRUCTION FOR USE OF LIQUID AIR EXPLOSIVES.[a]

I. USE OF LIQUID AIR FOR BLASTING.

1. The ceaseless consumption of all raw materials for war purposes makes the widest possible use of liquid air for explosives very desirable (reference given to other instructions); liquid air can be used with advantage in the construction of communication tunnels and dugouts, the driving of mine galleries, the rapid construction of shelter and communication trenches, etc., and for the destruction of all classes of obstacles.

2. Liquid air is specially useful for underground work, owing to the fact that no noxious gases are formed, consequently work can be resumed immediately after a blast.

3. The special precautions required in transporting and storing all other explosives are not necessary with liquid air explosives, as the actual explosive is only prepared in situ immediately before use.

4. The use of liquid air and its accessories does not entail the expenditure of any material otherwise required for munitions. The use of liquid air explosives therefore saves German raw material.

II. THE EXPLOSIVE.

5. The actual explosive is prepared immediately before use by the combination of two ingredients. These consist of liquid air and some carbonaceous material. The explosive is formed only when the carbonaceous material is soaked in the liquid air.

THE LIQUID AIR.

6. The liquid air used for explosives is a light blue liquid. It has a temperature of —180° (C.) and contains at least 95 per cent oxygen and not more than 5 per cent nitrogen. The active material is the oxygen.

7. The liquid air is transported and stored in transport flask.[b] For use the liquid air is poured into a pail by means of a funnel. The precautions necessary for the handling of liquid air are dealt with under "Safety precautions."

THE CARBONACEOUS MATERIAL.

8. The carbonaceous material used is a combustible material containing carbon and capable of absorbing many times its weight of liquid air.

9. The properties of the explosive can be varied by using different carbonaceous materials, and by a suitable choice it is possible to imitate the properties of most of the ordinary explosives.

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[a] Abstract from reports on enemy ammunition, No. 91, London, April 1, 1918; a translation of a German document dated Brussels, January 27, 1917, by Dr. Lespius. Supplement to Instructions for Explosives No. 5 (Ergänzung zur Sprengvorschrift Spr. V.). Instructions for Blasting with Liquid Air. Staff of the 1st Royal Prussian Pioneer School.

[b] Rough pencil sketches sent with the report are not reproduced here. They showed the flask, pail, etc., as double-walled glass vessels on the principle of the Thermos flask.

10. The material is chosen from the following:

Powdered cork, soot, sawdust, powdered straw, or other similar powdered or crushed materials. These are used either alone, or mixed with each other, or with other inactive material. They are made up into cartridges with a paper, cotton, or similar permeable container.

11. Liquid air in which no cartridges have been dipped, and cartridges which have not been soaked in liquid air, are not explosive and therefore are perfectly safe. Cartridges that have been soaked in liquid air are explosive and must be handled with all the precautions applicable to any other class of explosive.

III. DETONATING.

12. The firing of liquid air cartridges can be carried out by electric detonators, safety fuse and cap, or by the transmission of the detonation from one cartridge to another.

13. The ordinary electric detonator can be used, but the special liquid air electric detonator is preferable. For detonating by safety fuse the special liquid air fuse and cap should always be used.

FIRING BY SAFETY FUSE.

14. Safety fuse should be used in damp galleries where there is any danger of leakage from electric light or power mains firing the electric detonator. The instructions in "Explosives Instructions No. V" are generally applicable, but special liquid air fuse must be used and not ordinary safety fuse.

15. The *liquid air fuse* is used in conjunction with a cap, and here again a special liquid air cap must be used, and not the ordinary cap.

ELECTRIC DETONATING.

16. Except in special cases (see 13) liquid air cartridges are detonated electrically. The instructions No. V 56 et seq. are generally applicable. The arrangement of leads and of the exploder is the same.

17. It is even more important with liquid air cartridges than with ordinary explosives, to use the "Exploder"[a] and not to attempt to fire with accumulators, or lamp batteries, as these sources of current can not be relied on to fire the liquid air cartridges. For this purpose the sudden powerful current from the exploder is necessary.

18. For electrical firing of liquid air cartridges the special liquid air electric detonators should be used.

TRANSMISSION OF DETONATION.

19. The instructions No. V are generally applicable when one cartridge is to be detonated from another.

20. When several cartridges are to be detonated in a bore hole from one detonator, the cartridge containing the detonator is the last inserted.

IV. BLASTING.

21. The instructions for blasting given in Instruction No. V are generally applicable. The differences in procedure are given below. The chief difference between blasting with ordinary explosives and with liquid air explosives lies in the fact that the life of a liquid air cartridge is limited. With ordinary

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[a] See R. E. A. 81 G.

cartridges the time elapsing between laying and firing the charge is immaterial. With liquid air explosives this time is strictly limited. The explosive is formed by the absorption of liquid air by the carbonaceous material (see 5). As a result the cartridge is cooled to a temperature of —180° C. The liquid air cartridge is naturally warmed by the rock or other material that is to be demolished, with the result that the liquid air evaporates rapidly. If, owing to this evaporation, there is insufficient liquid air remaining, the cartridge can no longer be detonated. In the case of an ordinary bore hole, using cartridges 30 mm. in diameter there will be insufficient liquid left after about one-fourth hour. Rapid working is therefore essential, and it is necessary to carry out all preparations as far as possible before inserting the cartridges. This disadvantage, however, has a corresponding advantage, as all possibility of exploding such a cartridge has vanished after one-half hour, consequently the dangers that arise from the misfire of an ordinary cartridge are nonexistent with liquid air cartridges.

22. Even more rapid working is essential in order to obtain the chief advantage of liquid air explosives—viz, the absence of noxious gases. Liquid air explosive is the only explosive that works with an excess of oxygen, so that no carbon monoxide is formed, but only carbon dioxide. In order to ensure this, however, it is necessary to fire the charge not later than five minutes after the removal of the cartridges from the soaking vessel. (See 32.)

23. For soft-stone soot, and for hard-stone powdered cork, or mixed soot and cork, cartridges are used. The best type of cartridges must be determined by experience.

24. For demolitions with untamped charges the instructions for explosives (No. V) apply, due regard being paid to the principle of the use of liquid air explosives given in this supplement.

THE BORE HOLE.

25. It is possible to use fewer bore holes with liquid air than with ordinary explosives. It is, however, necessary to insure that the borehole is straight and of even diameter. It must have a diameter about 2 mm. greater than that of the cartridge. The diameter of the cartridge can sometimes be adjusted to that of the bore hole. Cartridges of specified diameter can be supplied on demand. It must be free from dirt so that the cartridge is not torn while being inserted.

26. The bore hole can be driven by hand or machine rotary drills, or by hand drills with a hammer or machine percussion drills.

INSERTING THE ELECTRIC DETONATOR.

27. The electric detonator is next inserted in the cartridge. To do this the thread closing the cartridge is untied and the detonator pushed in with a turning motion until its upper end is about 1 cm. below the thread. The thread is then tied in such a manner that only the electric leads project.

INSERTING THE SPECIAL FUSE.

28. The special liquid air fuse is first inserted into the liquid air cap and secured by squeezing the cap with a pair of pliers.

29. The cap is then inserted in the cartridge in the same way as the electric detonator (see 27) and the thread tied, so that only the fuse projects from the cartridge.

SOAKING THE CARTRIDGE.

30. The cartridge must now be carefully soaked with liquid air, this process making it actually explosive.

31. The vessel in which the cartridges are to be soaked is first filled about one-third full of liquid air. The necessary number of cartridges (with or without detonators, as required) are inserted in the vessel and slowly immersed. Only such a number of cartridges as can be easily inserted and withdrawn is to be placed in the vessel. More liquid air is then poured in till the cartridges are fully submerged. Finally the vessel is filled to the brim with liquid air. After a further five minutes the cartridges are ready for use.

32. The cartridges are withdrawn for the purpose of placing in the bore hole by means of wooden tongs. With some practice the use of the wooden tongs can be dispensed with.[a]

Gloves should not be worn when working with liquid air, as if the gloves absorb liquid air this will remain longer in contact with the skin, and cause serious injury. As in the case of ordinary explosives the fuse or leads must not be pulled or roughly handled, or its functioning will be interfered with.

CHARGING.

33. No unnecessary time must be spent in charging, if the advantage of liquid air explosives are to be realized. The cartridges are removed from the soaking vessel and placed in the bore hole, care being taken that the detonator or fuse is not damaged. The cartridges are pushed home into the bore hole with a wooden rammer. When several cartridges are used the one with the detonator is inserted last.

34. Care must be taken that the cartridges are not pressed hard in, or the liquid air will be squeezed out.

TAMPING.

35. Tamping is carried out with a wooden rammer whose diameter is only slightly smaller than that of the bore hole.

36. Tamping plugs of moist clay, or drillings from the bore hole or similar material, must be prepared before bringing up the charge, and placed in readiness close to the bore hole. The tamping plug next the charge is preferably of paper, wood-wool, grass or similar material, to allow for the evaporation of the liquid air caused by the warming effect of the rock. For the same reason the tamping must not be rammed tight. The tamping plugs are pushed in by the wooden rammer just sufficiently to touch each other, and only pressed just enough to fill the bore hole.

37. Metal tamping should on no account be used.

FIRING.

38. Firing differs from the use of ordinary explosive in that it must be done within a given time. With a bore hole of 30 mm. diameter and a length of charge of 280 mm. the charge must be fired at latest within five minutes of removing the cartridges from the liquid air vessel. It is necessary, therefore, to make all preparations for firing, clearing the gallery, etc., beforehand.

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[a] TRANSLATOR'S NOTE.—It is not understood how the use of the tongs can be dispensed with. The original says: "Bei einiger Uebung kann man auf die holzerne Zange verzichten."

V. THE EQUIPMENT.

FLASKS FOR TRANSPORTING LIQUID AIR.

39. The flasks for transporting the liquid air are double-walled spherical flasks with long necks. The inner wall projects somewhat through the outer to make a spout for pouring. The space between the walls is pumped free from air in order to prevent the conduction of heat, and to reduce the consequent evaporation of the liquid air.

To guard against external injury the spherical flask is protected by a sheet-metal case, provided with feet, handles, and lid. The lid is perforated in order to permit the escape of the evaporated air, which can not be entirely prevented; it is intended to prevent foreign bodies from entering the flask, and should be kept closed except when the liquid air is actually being poured in or out. The flask must not be closed by any other means.

40. The normal transport flask contains 15 liters when full, and loses 15 c.c. of liquid air per hour by evaporation.

THE VESSEL FOR SOAKING THE CARTRIDGES.

41. The vessel for soaking the cartridges consists of a double-walled bucket. The space between the walls is pumped free of air for the same reason as in the case of the transport flask. It is protected from external injury by a sheet-metal case provided with a handle. It is closed by a cover, with a hole in it to allow for the evaporation of the liquid air. It should normally be kept closed, and only opened for pouring in or out the liquid air, or for inserting or withdrawing the cartridges. Under no circumstances is any other method of closing the vessel to be used.

42. Any liquid air remaining after the soaking of the cartridges should be poured back into the transport flask by aid of the funnel.

THE FUNNEL.

43. The funnel consists of a narrow tube of base metal, that can be introduced into the neck of the transport flask till it is supported by a crosspiece fixed near the upper end. The top of the tube terminates in a funnel-shaped extension into which the liquid air is poured, and which is provided with a cover. Care must be taken not to touch the bare and extremely cold metal tube after using the funnel. The walls of the funnel proper and its handles are protected from the extreme cold by painting.

THE CARTRIDGES.

44. The cartridge consists of a shell of cotton or paper and is filled with the carbonaceous material (8). One end of the cartridge is closed, the other can be opened, in order to insert the detonator, by untying the knot.

THE LIQUID AIR ELECTRIC DETONATOR.

45. The liquid air electric detonator is similar to the ordinary electric detonator and consists as usual of a platinum fuse wire connected to the insulated copper wires and the igniting material. Unlike the ordinary fuse it contains no detonating material; it is completed by a perforated papier-mâché case or a slotted metal case filled with powdered cork. The liquid air detonator only becomes active after soaking in liquid air. Unsoaked it can not be detonated. The precautions necessary in handling ordinary detonators are therefore not necessary, but it should be protected from damp.

LIQUID AIR SAFETY FUSE.

46. The ordinary fuse should not be used with liquid air cartridges, as when soaked with liquid air it burns rapidly (1 cm. per sec.) owing to its braiding of vegetable fiber. The braiding of the special liquid air fuse is specially prepared so as not to burn.

47. The liquid air fuse is pushed into the liquid air detonating cap, which is made of iron and has a slit down the side to allow the liquid air to enter. The liquid air detonating cap only becomes active after soaking in liquid air. Until it has absorbed liquid air it can not be detonated, consequently the precautions necessary in handling ordinary explosives are not necessary. The detonators must, however, be guarded from damp.

THE WOODEN TONGS.

48. The tongs are used for withdrawing the cartridges from the soaking vessel and inserting them in the bore hole; in consequence of the soaking in liquid air they are intensely cold. They are provided with grooves to take the rounded cartridges. A spring is provided for ease of handling. With some practice the tongs can be dispensed with.[a]

VI. SAFETY PRECAUTIONS.

49. All rules to insure safety in the use of ordinary explosives must also be rigidly observed when blasting with liquid air. This applies especially to the handling of the detonators and fuses, the guarding of open flames in the galleries, and the safety of the men working from the effect of the blast. One must not be lulled into a false sense of security during the blasting, as the immunity from danger in storing and transporting the liquid air and the liquid air cartridges ceases when the cartridges have absorbed the liquid air; they are then just as dangerous as any other explosive.

TRANSPORT AND STORAGE OF LIQUID AIR.

50. The liquid air is transported and stored in the transport flasks. The flasks must be guarded from unnecessary warmth and also from rain, in order to insure a minimum of loss.

51. When not in use the flasks must be closed by the perforated lid. *No other* method of closing the flasks is to be used *under any circumstances*. The flasks should always be placed in a *vertical* position.

52. After the blast, any liquid air remaining in the soaking vessel is to be *poured back* into the transport flask by means of the funnel; care must be taken not to pour in any dirt with it.

TRANSPORT AND STORAGE OF THE CARTRIDGES.

53. The cartridges must always be guarded from damp and should be stored as far as possible in dry places. Damp cartridges do not absorb sufficient liquid air, and have therefore a restricted life.

54. The cartridges are perfectly safe until they have absorbed the liquid air. When they have absorbed the liquid air they are explosive and the same precautions must be taken as with other explosives.

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[a] See note to 32. The original says: "Bei einiger Uebung kann man auf die Anwendung der Zange verzichten."

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TRANSPORT AND STORAGE OF FUSES AND DETONATORS.

55. The fuses and detonators must be kept dry. Moisture renders them less certain in their action.

56. Unsoaked they are safe. After absorbing the liquid air they are explosive, and the same precautions must be taken as with other explosives.

CARE OF SOAKING VESSEL.

57. The inner walled portion of the soaking vessel is made of porcelain. It must therefore be carefully handled, not be thrown about, and always put down in an upright position. When not in use, and when cartridges are actually soaking, it must be closed with the perforated cover. On no account is any other form of covering to be adopted.

58. Vessels in which cartridges are being soaked, are explosive, and must be handled accordingly.

SOAKING.

59. Soaking the cartridges must be carried out with care, as insufficiently soaked cartridges may be a source of danger.

MISFIRE.

60. If a misfire is not due to insufficient absorption of liquid air (31?), it is generally caused by the detonators or leads being damaged. In any case, the bore hole must not be approached for half an hour. Also no strain should be put on the leads. After the lapse of half an hour so much liquid air will have evaporated that an explosion is impossible. Consequently any cartridges left in situ can be ignored in any further work.

PUBLICATIONS ON INVESTIGATIONS OF EXPLOSIVES.

A limited supply of the following publications of the Bureau of Mines has been printed and is available for free distribution until the edition is exhausted. Requests for all publications can not be granted, and to insure equitable distribution applicants are requested to limit their selection to publications that may be of especial interest to them. Requests for publications should be addressed to the Director, Bureau of Mines.

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PUBLICATIONS AVAILABLE FOR FREE DISTRIBUTION.

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Bulletin 48. The selection of explosives used in engineering and mining operations, by Clarence Hall and S. P. Howell. 1914. 50 pp., 3 pls., 7 figs.

Bulletin 59. Investigations of detonators and electric detonators, by Clarence Hall and S. P. Howell. 1913. 73 pp., 7 pls., 5 figs.

Bulletin 66. Tests of permissible explosives, by Clarence Hall and S. P. Howell. 1913. 313 pp., 1 pl., 6 figs.

Bulletin 80. A primer on explosives for metal miners and quarrymen, by C. E. Munroe and Clarence Hall. 1915. 125 pp., 51 pls., 17 figs.

Technical Paper 6. The rate of burning of fuse as influenced by temperature and pressure, by W. O. Snelling and W. C. Cope. 1912. 28 pp.

Technical Paper 7. Investigations of fuse and miners' squibs, by Clarence Hall and S. P. Howell. 1912. 19 pp.

Technical Paper 12. The behavior of nitroglycerin when heated, by W. O. Snelling and C. G. Storm. 1912. 14 pp., 1 pl., 2 figs.

Technical Paper 18. Magazines and thaw houses for explosives, by Clarence Hall and S. P. Howell. 1912. 34 pp., 1 pl., 5 figs.

Technical Paper 52. Permissible explosives tested prior to March 1, 1913, by Clarence Hall. 1913. 11 pp.

Technical Paper 69. Production of explosives in the United States during the calendar year 1912, compiled by A. H. Fay. 1914. 8 pp.

Technical Paper 71. Permissible explosives tested prior to January 1, 1914, by Clarence Hall. 1914. 12 pp.

Technical Paper 78. Specific-gravity separation applied to the analysis of mining explosives, by C. G. Storm and A. L. Hyde. 1914. 14 pp.

Technical Paper 89. Coal-tar products and the possibility of increasing their manufacture in the United States, by H. C. Porter, with a chapter on coal-tar products used in explosives, by C. G. Storm. 1915. 21 pp.

TECHNICAL PAPER 100. Permissible explosives tested prior to March 1, 1915, by S. P. Howell. 1915. 16 pp.

TECHNICAL PAPER 125. The sand test for determining the strength of detonators, by C. G. Storm and W. C. Cope. 1916. 68 pp., 2 pls., 5 figs.

TECHNICAL PAPER 145. Sensitiveness to detonation of trinitrotoluene and tetranitromethylanilin, by G B. Taylor and W. C. Cope. 1916. 11 pp.

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TECHNICAL PAPER. 169. Permissible explosives tested prior to January 1, 1917, by S. P. Howell. 1917. 19 pp.

TECHNICAL PAPER. 175. Production of explosives in the United States during the calendar year 1916, compiled by A. H. Fay. 1917. 24 pp.

TECHNICAL PAPER 192. Production of explosives in the United States during the calendar year 1917, with notes on coal-mine accidents due to explosives and list of permissible explosives tested prior to April 30, 1918, compiled by A. H. Fay. 1918. 21 pp.

MINERS' CIRCULAR 7. Use and misuse of explosives in coal mining, by J. J. Rutledge, with a preface by J. A. Holmes. 1913. 52 pp., 8 figs.

MINERS' CIRCULAR 19. The prevention of accidents from explosives in metal mining, by Edwin Higgins. 1914. 16 pp., 11 figs.

PUBLICATIONS THAT MAY BE OBTAINED ONLY THROUGH THE SUPERINTENDENT OF DOCUMENTS.

BULLETIN 10. The use of permissible explosives, by J. J. Rutledge and Clarence Hall. 1912. 34 pp., 5 pls., 4 figs. 10 cents.

BULLETIN 15. Investigations of explosives used in coal mines, by Clarence Hall, W. O. Snelling, and S. P. Howell, with a chapter on the natural gas used at Pittsburgh, by G. A. Burrell, and an introduction by C. E. Munroe. 1911. 197 pp., 7 pls., 5 figs. 25 cents.

BULLETIN 151. The analysis of black powder and dynamite, by W. O. Snelling and C. G. Storm. 1913. 80 pp., 5 pls., 5 figs. 10 cents.

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